SYSTEM AND METHOD FOR READING DATA STORED ON A MAGNETIC SHIFT REGISTER

CROSS-REFERENCE TO RELATED APPLICATION

The present application is related to co-pending U.S. patent applications Serial No. 10/458,554, titled "Shiftable Magnetic Shift Register and Method of Using the Same," and Serial No. 10/458,147, titled "System and Method for Writing to a Magnetic Shift Register," both of which were filed on June 10, 2003, and are incorporated herein by reference in their entirety.

FIELD OF THE INVENTION

The present invention generally relates to memory storage systems, and particularly to a memory storage system that uses the magnetic moment of magnetic domains to store data. Specifically, the present invention relates to a system that uses fringing fields associated with domain walls for reading data stored in a memory storage system.

BACKGROUND OF THE INVENTION

The two most common conventional non-volatile data storage devices are disk drives and solid state random access memories (RAM). Disk drives are capable of inexpensively storing large amounts of data, i.e., greater than 100 GB. However, disk drives are inherently unreliable. A hard drive includes a fixed read/write head and a moving medium upon which data is written. Devices with moving parts tend to wear out and fail. Solid state random access memories currently store data on the order of 1 GB (gigabyte) per device, and are relatively expensive, per storage unit compared to a disk drive.

The most common type of solid state RAM is Flash memory. Flash memory relies on a thin layer of polysilicon that is disposed in oxide below a transistor's on-off control gate. This layer of polysilicon is a floating gate, isolated by the silicon from the control gate and the transistor channel. Flash memory is relatively slow, with reading and writing times on the order of a microsecond. In addition, flash memory cells can begin to lose data after less than a million write cycles. While this may be adequate for some applications, flash memory cells would begin to fail rapidly if used constantly to write new data, such as in a computer's main memory. Further, the access time for flash memory is much too long for computer applications.

Another form of RAM is the ferroelectric RAM, or FRAM. FRAM stores data based on the direction that ferroelectric domains point. FRAM has access times much faster than Flash memory and consumes less energy than standard dynamic random access memory (DRAM). However, commercially available memory capacities are currently low, on the order of 0.25 MB (megabyte). In addition, memory storage in a FRAM relies on physically moving atoms, leading to eventual degradation of the medium and failure of the memory.

Yet another form of RAM is the Ovonic Unified Memory (OUM), which utilizes a material that alternates between crystalline and amorphous phases to store data. The material used in this application is a chalcogenide alloy. After the chalcogenide alloy experiences a heating and cooling cycle, it can be programmed to accept one of two stable phases: polycrystalline or amorphous. The differences in the respective resistances of the two phases allows the chalcogenide alloy to be used as memory storage. Data access time is on the order of 50 ns. However, the size of these memories is still small, on the order of 4 MB currently. In addition, OUM relies on physically changing a material from crystalline to amorphous; which likely causes the material to eventually degrade and fail.

Semiconductor magnetoresistive RAM (MRAM) encodes data bits in a ferromagnetic material by utilizing the direction of the material's magnetic moment. Atoms in ferromagnetic materials respond to external magnetic fields, aligning their magnetic moments to the direction of the applied magnetic field. When the field is removed, the atoms' magnetic moments still remain aligned in the induced direction. A field applied in the opposite direction causes the atoms to realign themselves with the new direction. Typically, the magnetic moments of the atoms within a volume of the ferromagnetic material are aligned parallel to one another by a magnetic exchange interaction. These atoms then respond together, largely as one macro-magnetic moment, or magnetic domain, to the external magnetic field.

One approach to MRAM uses a magnetic tunneling junction as the memory cell. The magnetic tunneling junction comprises two layers of ferromagnetic material separated by a thin insulating material. The direction of the magnetic domains is fixed in one layer. In the second layer, the domain direction is

allowed to move in response to an applied field. Consequently, the direction of the domains in the second layer can either be parallel or opposite to the first layer, allowing the storage of data in the form of ones and zeros. However, currently available MRAM can only store up to 1 Mb (megabit), much less than needed for most memory applications. Larger memories are currently in development. In addition, each MRAM memory cell stores only one bit of data, thereby limiting the maximum possible memory capacity of such devices.

What is needed is a magnetic shift register that replaces many conventional memory devices, including but not limited to magnetic recording hard disk drives, and many solid state memories such as DRAM, SRAM, FeRAM, and MRAM. The magnetic shift register should provide capacious amounts of storage comparable to those provided in conventional memory devices but without any moving parts and at a cost comparable to hard disk drives.

What is also needed is a reading device capable of selective reading of the data bits that have been stored in the shift register in small discrete regions, or domains, of a magnetic material. This reading device should be able to read the data stored in a magnetic shift register by detecting the direction of the magnetic moment of the domain of interest. The reading device should be able to read a magnetic moment direction by an external command or control. The need for such a reading device has heretofore been unsatisfied.

SUMMARY OF THE INVENTION

The present invention satisfies this need, and presents a system and an associated method (collectively referred to herein as “the system” or “the present system”) for a magnetic shift register, writing device, and reading device. Briefly, the present system uses the inherent, natural properties of the domain walls in ferromagnetic materials to store data. The present system utilizes one read/write device to access numerous bits, on the order of 100 bits of data or more. Consequently, a small number of logic elements can access hundreds of bits of data.

The present system uses spin based electronics to write and read data in ferromagnetic material so that the physical nature of the material in the magnetic shift register is unchanged. In one embodiment, a shiftable magnetic shift register comprises a data track formed of a fine wire or strip of material made of ferromagnetic material. The wire may be comprised of a physically uniform, magnetically homogeneous ferromagnetic material or layers of different ferromagnetic materials. Information is stored as direction of magnetic moment within the domains in the track. The wire can be magnetized in small sections in one direction or another.

An electric current is applied to the track to move the magnetic domains, along the track, in the direction of the electric current, past reading or writing elements or devices. In a magnetic material with domain walls, current passed across the domain wall moves the domain wall in the direction of the current flow. As the current passes through a domain, it becomes “spin polarized”. When this spin polarized current passes into the next domain across a domain wall, it develops a spin torque. This spin torque moves the domain wall. Domain wall velocities can be very high, on the order of 100 m/sec.

In summary, current passed through the track (having a series of magnetic domains with alternating directions) can move these domains past the reading and writing elements. The reading device can then read the direction of the magnetic moments. The writing device can change the direction of the magnetic moments, thus writing information to the track.

According to a preferred embodiment of the present invention, one read/write element is dedicated to a single track, with the understanding that in other embodiments, more than one read and/or write elements may be assigned to one or more tracks.

Associated with each domain wall are large magnetic fringing fields. The domain wall concentrates the change in magnetism from one direction to another in a very small space. Depending on the nature of the domain wall, very large dipolar fringing fields can emanate from the domain wall. This characteristic of magnetic domains is used to write to the magnetic shift register. When the domain wall is moved close to another magnetic material, the large fields of the domain wall change the direction of the magnetic moment in the magnetic material, effectively "writing" to the magnetic material.

An important characteristic of domain wall fringing fields is that they are localized in small regions of space near the domain wall. Thus, domain wall fringing fields can provide highly localized and large magnetic fields that can be manipulated in space by moving or controlling the position of the domain wall within a magnetic entity such as a magnetic wire. Since the magnitude of the fringing fields drops rapidly with distance from the domain wall, application of the domain wall fringing fields can be controlled in wires by varying the distance

of the wire from the material, whose property is to be changed by the domain wall fringing field and by moving the domain wall along the wire.

This concept of using fringing fields to write to a magnetic material can be applied to many different applications, such as magnetic random access memories; magnetic recording hard disk drives; magnetic logic devices; security cards using magnetically stored information; semiconductor devices wherein large magnetic fields provided by domain wall fringing fields can be used to locally vary the electronic properties of the semiconductor or semiconductor heterostructure; and mesoscopic devices, which are sufficiently small that the electronic energy levels therein, can be substantially affected by the application of local magnetic fields.

For applications involving the manipulation of spin-polarized current in semiconductors, spin-polarized current is injected into a semiconductor or semiconductor heterostructure, and then is manipulated as desired, according to the specific application in which the present invention is used. If a very large local magnetic field is applied to the semiconductor, certain electronic levels in the semiconductor can be spin-split, changing the electronic state of the semiconductor. For example, the electronic state of the semiconductor can be changed from being conductive to being non-conductive. Consequently, the use of a device such as the fringing field write device can be used to switch a semiconductor from "on" to "off".

The influence of a magnetic field on a semiconductor or semiconductor heterostructure is determined, in large part, by the gyromagnetic ratio, g-factor, of the semiconductor. The larger the g-factor, the larger is the effect of the magnetic field on the electronic properties of the semiconductor. So, it may be

advantageous to use the present system in conjunction with semiconducting materials with large g-factors.

Reading the data on the magnetic shift register can be accomplished, for example, using a magnetic tunneling junction. A magnetic tunneling junction has two magnetic materials separated by a very thin insulating layer, or tunneling barrier. The magnitude of any current passed through the tunneling barrier depends on the relative magnetic orientation of the two magnetic materials in the tunneling junction. Consequently, the value of the current in the tunneling junction indicates the direction of the magnetic moment in the magnetic shift register that is being read. For further details about the design and performance of the magnetic tunneling junction and the exchange biased magnetic tunnel junction, reference is made to U.S. Patent Nos. 5,650,958; 5,729,410; and 5,801,984, which are incorporated herein by reference.

By incorporating the magnetic shift register as part of the magnetic tunneling junction, information stored in the domains in the magnetic shift register is read by the current that passes through the magnetic tunnel junction. As the domains flow pass the magnetic tunneling junction, the magnitude of the current indicates the value stored by the direction of the domain. Moving the domains around the magnetic shift register brings the chosen domain to the magnetic tunneling junction for reading purposes.

In another embodiment of the current application the reading device is a device separate from the magnetic shift register but situated in proximity thereto. The placement of the reading device is such that the domain wall fringing fields emanating from the domains in the magnetic shift register can be used to change the magnetic state of the reading device as the magnetic domains in the shift register pass by the reading device.

The reading device is electrically isolated from the magnetic shift register, and is situated at a distance greater from the magnetic shift register than is possible if the reading device electrically incorporates part of the magnetic shift register itself. The reading device accesses the state of the magnetic bits within the magnetic shift register by sensing the magnetic fringing fields from the domain walls in the magnetic shift register within which the magnetic bits are encoded. One embodiment of the electrically isolated reading device comprises two layers of magnetic material. The first layer is a pinned layer that is magnetically hard. The magnetic moment of the pinned layer does not change when the fringing field of the domain wall is applied to it.

The second layer is a free layer that is magnetically soft. The magnetic moment of the free layer changes when the fringing field of the domain wall is applied to it. Consequently, a fringing field of one direction changes the direction of the magnetic moment of the free layer, causing the magnetic moments of the free layer and the pinned layer to be oriented parallel to each other.

A fringing field of the opposite direction causes the magnetic moments of the free layer and the pinned layer to be oriented anti-parallel to each other. When the magnetic moments of the free and pinned layer are aligned in parallel, the resistance of the reading device is low. Conversely, when the magnetic moments of the free and pinned layer are anti-parallel to each other, the resistance of the reading device is high. It is also possible that the magnetic tunnel junction can display higher resistance when the magnetic moments of the pinned and free layers are parallel to one another than when they are anti-parallel but the principle of operation of the reading device is the same.

The relative alignment of the pinned and free layers can thus be determined by, for example, passing a current through the reading device and measuring the resulting potential. A low voltage implies a low resistance and thus that the pinned and free layers are parallel. A high voltage implies a high resistance and thus that the pinned and free layers are anti-parallel.

The reading device can be sensed either by applying a constant voltage across the reading device and measuring the current through the device or by passing a constant current through the device and measuring the voltage drop across the device. Consequently, the voltage drop across the reading device or the current passing through the device indicates the direction of the magnetic fringing field from the magnetic domain walls between oppositely magnetized domains in the magnetic shift register, thereby, reflecting the data stored in the magnetic shift register. The storage of digital data in the magnetic shift register in the form of the domain walls between magnetic domains is analogous to the storage of data in magnetic media in conventional longitudinal magnetic recording disk drives.

The state of the domains in the magnetic shift register is read by reading the magnetic state of the domain wall between magnetic domains. This enables the reading of the domains very quickly. The reading device can operate in either a static or dynamic mode.

In the dynamic mode the domain wall fringing field is moved across the reading device so that the free magnetic layer of the magnetic junction responds and the change in resistance of the MTJ reading device allows the magnetic bit to be read. In the static mode of reading, the domain wall fringing fields are directed towards the MTJ reading device when the domain walls are not moving and the static resistance of the MTJ is measured.

By design, the separation or gap between the sensing or free layer of the magnetic tunneling junction of the reading device and the shift register is fixed such that the fringing fields from the domain walls in the shift register change the magnetic state of the free layer in the magnetic tunneling junction reading device.

The magnetic shift register described herein presents numerous advantages over other forms of solid state memory and magnetic recording hard disk drives. In particular, the magnetic shift register provides a means of accessing hundreds of data bits using a small number of logic gates and circuit elements. Thus, the magnetic shift register can provide capacious amounts of storage comparable to those provided in conventional hard disk drives but without any moving parts and at a comparable cost of such hard disk drives.

Similarly, compared to conventional solid state memory devices, the magnetic shift register provides far higher memory capacities but at a fraction of the cost per bit of conventional solid state memories. This advantage is achieved because the magnetic shift register can be fabricated using standard CMOS processes and methods of manufacture but the magnetic shift register stores hundreds of data bits for the same area of silicon in which a conventional CMOS solid state memory stores one or a small number of bits.

This latter advantage is realized because the magnetic shift register uses the third dimension out of the plane of the silicon substrate to store data in largely vertical tracks which occupy little space on the silicon substrate. Since the cost of CMOS logic and memory is largely determined by the area of silicon used in any given technology node the magnetic shift register can thereby

provide a far cheaper means of storing data than conventional solid state memories.

The magnetic shift register can thus be used to replace many existing data storage devices, including but not limited to magnetic recording hard disk drives, and many solid state memories such as DRAM, SRAM, FeRAM, and MRAM.

The capacity of the magnetic shift register can be varied over a wide range continuously by simply varying the number of magnetic shift register tracks per memory device. This is a particular advantage over magnetic hard disk drives in which, because of the high cost of the reading and writing heads and their circuitry, and the high cost of the mechanical means of moving these heads and the magnetic media, a hard disk drive only provides an inexpensive means of storage when many gigabytes of data are stored, such that the cost of the mechanical components of the hard disk drive is amortized over the large number of data bits.

By contrast, the magnetic shift register can be built at low cost per bit in much smaller sizes, thereby allowing the magnetic shift register to be used for a wide range of applications where the data storage capacity required is much lower than that of a magnetic hard disk drive. Thus the magnetic shift register can be used for various electronic devices including by way of example, but not limited to: digital cameras, personal digital assistants, security devices, memory sticks, and removable storage devices.

BRIEF DESCRIPTION OF THE DRAWINGS

The various features of the present invention and the manner of attaining them will be described in greater detail with reference to the following description, claims, and drawings, wherein reference numerals are reused, where appropriate, to indicate a correspondence between the referenced items, and wherein:

FIG. 1 is comprised of FIGS. 1A and 1B, and represents an exemplary operating environment in which a writing element is used to write data to a magnetic shift register according to the present invention;

FIG. 2 is comprised of FIGS. 2A, 2B, and 2C and represents a schematic diagram illustrating a method of operation of the magnetic shift register of FIG. 1;

FIG. 3 is a process flow chart illustrating a method of operation of the magnetic shift register of FIG. 1.

FIG. 4 is comprised of FIGS. 4A and 4B, and represents a schematic diagram illustrating an embodiment of the magnetic shift register of FIG. 1 constructed of multiple types of alternating ferromagnetic materials;

FIG. 4C is a schematic diagram of another embodiment of the shift register of FIG. 1, illustrating a well or bottom section of the shift register as being composed of a single ferromagnetic material;

FIG. 5 is comprised of FIGS. 5A and 5B, and represents a schematic diagram illustrating an embodiment of the magnetic shift register of FIG. 1 constructed with indentations in a homogeneous ferromagnetic material;

FIG. 6 is a schematic diagram illustrating an embodiment with parallel connections of magnetic shift registers of FIG. 1;

FIG. 7 is a schematic diagram illustrating an embodiment with an array of magnetic shift registers of FIG. 1;

FIG. 8 is comprised of FIGS. 8A, 8B, 8C, 8D, and 8E, and represents schematic diagrams illustrating various embodiments of configurations of the magnetic shift register of FIG. 1;

FIG. 9 is comprised of FIGS. 9A, 9B, 9C, and 9D, and represents schematic diagrams illustrating various embodiments of placements for the writing and reading devices of the magnetic memory system of FIG. 1;

FIG. 10 is comprised of FIGS. 10A, 10B, and 10C, and represents a schematic diagram and two graphs illustrating fringing fields of the magnetic memory system of FIG. 1;

FIG. 11 is comprised of FIGS. 11A and 11B, and represents a schematic diagram of the writing device of FIG. 1;

FIG. 12 is a process flow chart illustrating a method of operation of the writing device of FIG. 1;

FIG. 13 is comprised of FIGS. 13A, 13B, and 13C, and represents a schematic diagram portraying a method of operation of the operation of the writing device of FIG. 1;

FIG. 14 is comprised of FIGS. 14A and 14B, and represents a configuration of an alternative embodiment of the writing device of FIG. 1, using a bend in the track of the writing device;

FIG. 15 is comprised of FIGS. 15A and 15B, and represents a configuration of an alternative embodiment of the writing device of FIG. 1, using a block of ferromagnetic material;

FIG. 16 represents a configuration of an alternative embodiment of the writing device of FIG. 1, using multiple types of ferromagnetic material;

FIG. 17 represents a configuration of an alternate embodiment of the writing device of FIG. 1, using indentations in a track of ferromagnetic material;

FIG. 18 is comprised of FIGS. 18A and 18B, and represents a configuration of the reading device of FIG. 1;

FIG. 19 is a diagram illustrating current flow through a configuration of the reading device of FIG. 1; and

FIG. 20 is a process flow chart illustrating a method of operation of the reading device of FIG. 1.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

FIG. 1 (FIGS. 1A and 1B) illustrates an exemplary high-level architecture of a magnetic memory system 100 comprising a magnetic shift register 10 that utilizes a writing device (also referred to herein as writing element) 15 and a reading device (also referred to herein as reading element) 20. Both the reading device 20 and the writing device 15 form a read/write element of system 100.

The magnetic shift register 10 comprises a fine track 11 preferably made of ferromagnetic or ferrimagnetic material. The track 11 can be magnetized in small sections, or domains, in one direction or another. Information is stored in regions such as domains 25, 30 in the track 11. The order parameter of the magnetic material from which the track is fabricated, that is the magnetization direction or the direction of the magnetic moment, changes from one direction to another. This variation in the direction of the magnetic moment forms the basis for storing information in the track 11.

In one embodiment, the magnetic shift register 10 comprises a data region 35 and a reservoir 40. The data region 35 comprises a contiguous set of domains such as domains 25, 30 that store data. Additional length is provided to the magnetic shift register 10 in the form of a reservoir 40.

The reservoir 40 is made sufficiently long so that it accommodates all the domains in the region 35 when these domains are moved completely from region 35 across the writing and reading elements for the purposes of writing and reading domains into region 40. At any given time, the domains are thus stored partially in region 35 and partially in region 40, so it is the combination of region 35 and region 40 that forms the storage element. In one embodiment, the reservoir 40 is devoid of magnetic domains in a quiescent state.

Thus, the storage region 35 at any given time may be located within a different portion of the magnetic shift register 10, and the reservoir 40 may be divided into two regions on either side of the storage region 35. Although the storage region 35 may be one contiguous region, the spatial distribution and extent of the domains within the storage region 35 may be approximately the same no matter where the storage region 35 resides within the shift register 10. In another embodiment portions of the storage region may be expanded during the motion of this region particularly across the reading and writing elements. A portion or all of the data region 35 is moved into the reservoir 40 to access data in specific domains.

The reservoir 40 is shown in FIG. 1 as approximately the same size as the data region 35. However, other alternative embodiments may allow the reservoir 40 to have a different size than the data region 35. As an example, the reservoir 40 is much smaller than the data region 35 if more than one reading and writing element are used for each magnetic shift register. For example, if two reading and writing elements are used for one shift register and are disposed equally along the length of the data region, then the reservoir only needs to be approximately half as long as the data region.

An electric current 45 is applied to the track 11 to move the magnetic moments within domains 25, 30, along the track 11, and past the reading device 20 or the writing device 15. In a magnetic material with domain walls, a current passed across the domain walls moves the domain walls in the direction of the current flow. As the current passes through a domain, it becomes "spin polarized". When this spin polarized current passes through into the next domain across the intervening domain wall, it develops a spin torque. This spin torque moves the domain wall. Domain wall velocities can be very high, i.e., on

the order of 100 m/sec, so that the process of moving a particular domain to the required position for the purposes of reading this domain or for changing its magnetic state by means of the writing element can be very short.

The domains, such as domains 25, 30, 31 are moved (or shifted) back and forth over the writing device 15 and reading device 20, in order to move the data region 35 in and out of the reservoir 40, as shown in FIG. 2 (FIGS. 2A, 2B, 2C). In the example of FIG. 2A, the data region 35 initially resides on the left side of the well, i.e., bottom section 32, of the magnetic shift register 10, with no domains in the reservoir 40. FIG. 2C shows the case where the data region 35 resides entirely on the right side of the magnetic shift register 10.

In order to write data in a specific domain, such as domain 31, a current 45 is applied to the magnetic shift register 10 to move domain 31 over, and in alignment with the writing device 15. All the domains in the data region 35 move when the current is applied to the magnetic shift register.

The movement of the domains is controlled by both the magnitude and direction of the current, and the time over which the current is applied. In one embodiment, one current pulse of a specified shape (magnitude versus time) and duration, is applied to move the domains in the storage region in one increment or step. A series of pulses are applied to move the domains the required number of increments or steps. Thus, a shifted portion 205 (FIG. 2B) of the data region 35 is pushed (shifted or moved) into the reservoir region 40. The direction of motion of the domains within the track 11 depends on the direction of the applied current.

In order to read data in a specific domain, such as domain 25, additional current is applied to the magnetic shift register 10 to move domain 25 over, and

in alignment with, the reading device 20. A larger shifted portion 210 of the data region 35 is pushed (shifted or moved) into the reservoir 40.

The reading and writing devices shown in FIGS. 1 and 2 form part of a control circuit that defines a reference plane in which the reading and writing devices are arrayed. In one embodiment, the magnetic shift register 10 stands vertically out of this reference plane, largely orthogonal to this plane.

In order to operate the magnetic shift register 10 the control circuit includes, in addition to the reading and writing elements, logic and other circuitry for a variety of purposes, including the operation of the reading and writing devices, the provision of current pulses to move the domains within the shift register, and the means of coding and decoding data in the magnetic shift register. In one embodiment the control circuit is fabricated using CMOS processes on a silicon wafer. The magnetic shift registers are preferably designed to have a small footprint on the silicon wafer so as to maximize the storage capacity of the memory device while utilizing the smallest area of silicon to keep the lowest possible cost.

In the embodiment shown in FIG. 1 the footprint of the shift register is determined largely by the area of the wafer that the reading and writing devices occupy. Thus, the magnetic shift register is comprised of tracks extending largely in the direction out of the plane of the wafer. The length of the tracks in the vertical direction determines the storage capacity of the shift register. Since the vertical extent can be much greater than the extent of the track in the horizontal direction hundreds of magnetic bits can be stored in the shift register, yet the area occupied by the shift register in the horizontal plane is very small. Thus, the shift register can store many more bits for the same area of silicon wafer as compared to conventional solid state memories.

Although the tracks of the magnetic shift register are shown as being largely orthogonal to the plane of the reading and writing elements (the circuitry plane) these tracks can also be inclined, at an angle, to this reference plane, as an example, for the purpose of greater density or for ease of fabrication of these devices.

A method 300 of operating the magnetic shift register 10 is illustrated in FIG. 3, with further reference to FIG. 2 (FIGS. 2A, 2B, and 2C). With reference to FIG. 2A, the memory system 100 determines, at block 305, the number of bits required to move domain 25 to either the writing device 15 or reading device 20. The memory system 100 also determines the direction required to move domain 25 in bock 310. In FIG. 2A, domain 25 is on the left of the writing device 15 and the reading device 20. A positive current 45 may be required to move domain 25 to the right, for example, while a negative current 45 may be required to move domain 25 to the left.

The memory system 100 then applies the desired current 45 to the magnetic shift register 10 at block 315. Current 45 may be one pulse or a series of pulses, moving the domain 25 one bit at a time. It is also possible to vary the length of duration or the magnitude of the current within the pulse or the pulse shape (current versus time within the pulse), to cause the domain 25 within the storage region 35 to move by several increments during the application of one pulse. The domains in the data region 35 move in response to the current 45 in block 320. Domain 25 stops at the desired device, i.e., writing device 15 or reading device 20 (block 325).

With reference to FIG. 4 (FIGS. 4A, 4B), an alternative magnetic shift register 10A may be similar to the shift register 10 of FIGS. 1 and 2, but is made

of alternating magnetic layers, to pin the possible locations of the domains within the magnetic shift register 10A. Pinning the possible locations of the domains prevents the designated domains from drifting.

The magnetic layers may be comprised of various ferromagnetic or ferrimagnetic materials where these magnetic materials are chosen appropriately based primarily on the magnitude of their magnetization (magnetic moment per unit volume), exchange parameter, magnetic anisotropy, and damping coefficient. The choice of these materials will also be influenced by their manufacturability and compatibility with the process used to fabricate the magnetic shift register.

As shown in region 405 of the shift register 10A, one type of magnetic material may be used for domains 410, 420, while a different type of magnetic material may be used for alternating domains 415, 425. In another embodiment, multiple types of magnetic materials may be used, in varying order of materials.

The introduction of different ferromagnetic layers in the magnetic shift register 10A creates local energy minima, similar to "potential wells", so that the domain walls between domains of opposite polarity will align themselves with the boundaries between the alternating ferromagnetic layers 410, 415, etc. Thus, the extent and size of the domains will be determined by the thicknesses of the magnetic layers.

A current pulse 45 applied to the magnetic shift register 10A causes the domains 410 - 425 within the region 405 to move in the direction of the current 45. However, unless the current pulse 45 is of sufficient amplitude and duration, the domains 410 - 425 may not move past the boundaries between the two different types of magnetic material. Consequently, the data region 35 can be

moved one bit at a time, and the domains are not allowed to drift past their desired positions.

In addition to pinning the possible locations of the domains, using different layers of magnetic material also allows higher tolerances for current amplitude and pulse duration. In this embodiment, the portion of the magnetic shift register 10A that passes over the writing device 15 and the reading device 20 can be a homogeneous magnetic material or layers of different magnetic materials as illustrated in FIG. 4C.

The length of the alternating magnetic regions 410, 420, etc. and 415, 425 etc. can be different. Moreover, although it may be preferred that the length of each type of magnetic region 410, 420, etc., and 415, 425, etc. be the same throughout the shift register, this is not essential, and these lengths can vary somewhat throughout the magnetic shift register. What is important is that the potential that pins the domains in their defined positions against current induced motion induced by the current pulses.

With reference to FIG. 5 (FIGS. 5A, 5B), another magnetic shift register 10B that is made of homogeneous magnetic material can be made inhomogeneous by physically varying the width or the area of the track 11. Local energy minima can be created within the magnetic shift register 10B by physically shaping the magnetic shift register 10B.

In the shaping approach of FIG. 5, indentations, such as indentations 505, 506, are introduced in the ferromagnetic material of the magnetic shift register 10B. The indentations 505, 506 may either be open or filled with a material that may be metallic or insulating.

In one embodiment, these indentations 505, 506 can be placed at uniform spacings. In another embodiment, the spacings between these indentations 505, 506 may be non-uniform along the length of the magnetic shift register 10B. The indentations 505, 506 are aligned with each other on either side of the track 11. However, it may be easier to fabricate a magnetic shift register with indentations on only one side of the track. Since these indentations 505, 506 are used to pin the domain walls, only one indentation on one side of the track may provide a sufficient pinning potential. Indeed, indentations may be situated on one or two or more of any of the four sides of the track shown in FIG. 5.

In another embodiment, the indentations may be replaced with extrusions where the width of the track is locally increased and not decreased. What is required is a means of pinning the domains by changing the local potential for the domain walls.

In yet another embodiment, the width or area of the wire may be alternated in successive regions so that the wire is comprised of regions of alternating widths or areas.

The magnetic shift register does not need to be uniformly filled with indentations or extrusions or alternating magnetic regions along its length. The magnetic shift register need only be filled with a sufficient number of such pinning sites, such that the storage region moves by only one, or a specified number of increments per current pulse. For example, only one pinning site per N domains may be sufficient where N may be more than 1.

The reservoir 40 may or may not include these indentations. A bottom section 510 of the magnetic shift register 10B that crosses the writing device 15 and the reading device 20 may or may not include these indentations 505, 506.

In a further embodiment, the magnetic shift register 10B may be made of a combination of different ferromagnetic materials with indentations 505, 506, combining the features of magnetic shift register 10A and 10B.

FIG. 6 illustrates a shift register 10AA according to another embodiment of the present invention. The shift register 10AA is comprised of a plurality of magnetic shift registers 10 (or a combination of other suitable shift registers described herein) that are connected in series. In this embodiment, the magnetic shift registers 10 are connected in series.

FIG. 7 illustrates a shift register 10BB according to yet another embodiment of the present invention. The shift register 10BB is comprised of a plurality of magnetic shift registers 10 (or a combination of other suitable shift registers described herein) that are connected in an array configuration. The array configuration is shown for example purpose only, as comprising three rows 705, 710, 715 of magnetic shift registers 10, with each row comprised of numerous shift registers 10. The shift registers 10 in each row are connected in series, while the various rows 705, 710, 715 are connected in parallel. The sections, i.e., 733, 734, that connect the magnetic shift registers 10 in one row, i.e., row 705, may be a high conductivity material such as copper, or a ferromagnetic material, such as that used in the magnetic shift array 10BB.

Although the magnetic shift registers, i.e., 10, described so far are shown to have a generally "U" shape, the shape of the magnetic shift registers is not limited to that shape. FIG. 8 (FIGS. 8A, 8B, 8C, 8D, 8E) illustrates various exemplary, non-limiting embodiments of the magnetic shift register 10.

With reference to FIG. 8A, a magnetic shift register 10C may be formed in a generally "W" shape. With reference to FIG. 8B, a magnetic shift register 10D may be formed in a generally semi-circular shape. With reference to FIG. 8C, a magnetic shift register 10E may be formed in a generally "V" shape. With reference to FIG. 8D, a magnetic shift register 10F may be formed in a generally "N" shape. With reference to FIG. 8E, a magnetic shift register 10G may be formed in a generally serpentine shape with the input current 45 and output connection 805 on the same plane as the writing device 15 and the reading device 20.

The magnetic shift register 10 may be formed in any shape that accomplishes the objective of shifting the magnetic domains as described herein. In addition, the placement of the writing device 15 and the reading device 20 is not limited to any particular position. As illustrative examples, the writing device 15 may be disposed either on the left side or the right side of the reading device 20. In FIG. 1, the writing device 15 is shown on the left of the reading device 20. In FIG. 8A, the writing device 15 is shown on the right of the reading device 20.

Although the figures show the reservoir 40 as being a continuous section of track 11, and the data region(s) 35 as being a continuous set of domains, the data region(s) 35 may also be a set of smaller data regions separated by smaller lengths of reservoir(s) 40.

FIG. 9 (FIGS. 9A, 9B, 9C, 9D) illustrates alternative embodiments for the placement of the writing devices 15 and the reading devices 20. Using, for example, a U-shape configuration for the magnetic shift register 10, the reading device 20 and writing device 15 may be placed on a lateral side 909 of the magnetic shift register 10 (FIG. 9A).

In the embodiment of FIG. 9B, the reading device 20 is disposed on the interior of lateral side 909, while the writing device 15 is disposed on the interior of lateral side 911. In addition, the reading device 20 and the writing device 15 may be placed at opposite ends of the magnetic shift register 10, or in alignment with each other. In another embodiment, one of the writing device 15 or the reading device 20 can be disposed on the exterior while the other device can be disposed on the interior of the magnetic shift register 10. In yet another embodiment, the reading device 20 and the writing device 15 are not disposed in alignment with each other.

The disposition of the writing and reading elements are chosen for ease of operation and manufacturability of the magnetic shift register. Moreover, the disposition of these elements, especially if the reading and writing elements are significantly displaced from one another, will affect the proportion of the magnetic shift register that can be occupied by the storage region. Separating the reading and writing elements significantly from one another along the shift register will reduce the size of the storage region in proportion of the total length of the shift register.

Multiple reading devices 20 and writing devices 15 may be used as shown in FIG. 9C. Although FIG. 9C shows equal numbers of reading devices 20 and writing devices 15, unequal numbers of each device may alternatively be used. These multiple reading devices 20 and writing devices 15 may be placed on opposite sides 909, 911 of the magnetic shift register 10, as shown in FIG. 9C.

Alternatively, the multiple reading devices 20 and writing devices 15 may be disposed, in an alternating relationship, on the same side, i.e., 909, of the magnetic shift register 10, as shown in FIG. 9D. It is preferred that the writing

and reading elements are located in close proximity to one another to maximize the extent of the storage region in proportion to the overall length of the magnetic shift register.

As previously presented, current 45 passed through a track 11 (having a series of domains with alternating directions) can move these domains past the writing device 15 or reading device 20. Associated with each domain wall is a large magnetic fringing field. The domain wall concentrates the change in magnetism from one direction to another in a very small space. Depending on the nature of the domain wall, a sufficiently large dipolar fringing field can emanate from the domain wall.

FIG. 10 (FIGS. 10A, 10B, 10C) illustrates the concept of domains, domain walls, and fringing fields, as used in conjunction with the present invention. FIG. 10A shows an exemplary magnetic material with two domains 1005 and 1010.

The arrows, such as arrow 1015, represent a magnetic moment, or dipole, and indicate local magnetization directions. The magnetic moments in domain 1005 point to the right, while the magnetic moments in domain 1010 point to the left. The domain wall 1020 is the region in which domains 1010, 1005 of opposite polarity meet. The change of magnetism between domain 1005 and domain 1010 is concentrated in the small domain wall 1020, creating a large dipolar fringing field emanating from the surface of the layer.

The relative magnitude of an exemplary fringing field B is shown in FIG. 10B. The fringing field B is localized and concentrated over a region of, for example, approximately 100 nm in the x dimension. The peak values of the components Bx, By, and Bz of the fringing field B, are illustrated in FIG. 10C as a function of out-of-plane distance. The fringing field is also localized in the z

direction, and is concentrated primarily in a region of approximately 20 nm in the z direction.

These fringing field components Bx, By, and Bz are very high in the region of the domain wall 1020, and drop off rapidly with distance from the domain wall 1020. Consequently, the fringing field B is localized and sufficiently large to magnetize a ferromagnetic material in a small region.

The fringing field B is used to read from and write onto the magnetic shift register 10. When the domain wall 1020 is moved close to another magnetic material, the large fringing field B of the domain wall 1020 changes the direction of the magnetic moment in the magnetic material, effectively "writing" to the magnetic material. This domain wall 1020 can be moved within the magnetic material by passing a current 45 through the magnetic material that is perpendicular to the domain wall 1020.

With reference to FIG. 11 (FIGS. 11A and 11B), the writing device 15 is comprised of a ferromagnetic track or wire 1105 that is placed in proximity to the magnetic shift register 10. As illustrated for exemplary purposes, the ferromagnetic track 1105 is comprised of a plurality of successive domains 1110, 1115, and 1120. These domains 1110, 1115, 1120 define domain walls 1125, 1130, therebetween.

A first domain wall 1125 is associated with fringing field 1135, and a second domain wall 1130 is associated with fringing field 1140. When one of the domain walls 1125 or 1130 of the writing device 15 passes the region closest to the magnetic shift register 10, the large magnetic field in the domain wall 1125 or 1130 of the writing device 15 can be used to write on the magnetic shift register 10.

In order to write to the magnetic shift register 10, the writing device 15 selectively changes the direction of the magnetic moment of a domain 1145 in the magnetic shift register 10. In the present illustration, the magnitude of the fringing field 1135 applied to the magnetic shift register 10 decreases rapidly outside the region around the domain wall 1125, either in the writing device 15 or the magnetic shift register 10. The magnitude of the fringing field applied by the writing device 15 to the magnetic shift register 10 can be controlled by controlling the relative location of the domain wall 1125 in the writing device 15. The location of the domain wall 1125 is controlled by applying a current 1150 (also referred to herein as current 45) to the writing device 15.

A method 1200 of the writing device for writing data according to the present invention, is illustrated by the process flow chart of FIG. 12, considered in conjunction with FIG. 13 (FIGS. 13A, 13B, 13C). The domain wall and its associated magnetic fringe fields are shown in a quiescent position outside a write region 1305 (FIG. 13B) of the writing device in FIG. 13. A request to write data is received by the memory system.

At block 1205 of FIG. 12, the memory system translates the data (0 or 1) into whether the domain 1145 receives a magnetic moment pointing right (a right magnetic moment) or a magnetic moment pointing left (a left magnetic moment). The magnetic moment direction of the domains can be either along the track direction or perpendicular to the track direction. For very narrow tracks the preferred direction of the magnetic moments will be along the track direction. If, at decision block 1210, the domain 1145 is to be written with a right magnetic moment, method 1200 proceeds to block 1215.

At block 1215, a current 1150 is applied to the writing device 15 in FIG. 13A, moving the domain wall 1125 in the positive direction (block 1220), as denoted by direction 1310. Consequently, fringing field 1135 is moved within the write region 1305 (FIG. 13B). The magnetic fringe field 1135 writes to the magnetic shift register 10 (block 1225), changing the direction of the magnetization of domain 1145 to point in the right direction.

The current 1150 is then applied to the writing device (block 1230) in a direction 1315 (FIG. 13C) that is opposite to the previous direction 1310, so that the writing device domain 1110 is returned to its quiescent position shown in FIG. 13A (block 1235).

The writing device domain wall 1125 remains in close proximity to the magnetic shift register 10 for only an instant (or a predetermined period) of time, that is sufficient to write to the domain 1145 of the magnetic shift register 10. The magnitude of fringing field 1135 that is applied to domain 1145 is large only when the domain wall 1125 of the writing device 15 is in proximity to the magnetic shift register 10.

If the domain 1145 is to be written with a left magnetic moment at decision block 1210, method 1200 proceeds to block 1240. At block 1240, a current 1150 is applied to the writing device 15, as illustrated in FIG. 13C, to cause the domain wall 1110 to move in the negative direction (block 1245), as denoted by the reference numeral 1315.

A fringing field 1140 is shifted within the write region 1305 (FIG. 13C). The magnetic fringe field writes to the magnetic shift register 10 (block 1250), changing the direction of the magnetization of domain 1145 to point in the left direction. A current 1150 is then applied to the writing device (block 1255), and

the writing device domain 1110 is returned to its quiescent position shown in FIG. 13A (block 1235).

In an alternative embodiment shown in FIG. 14 (FIGS. 14A, 14B), the domain walls 1125, 1130 (FIG. 13) can be brought even closer to the magnetic shift register 10 by means of an arch-shaped bend 1405 in a track 1410 of the writing device 15A. A current 1415 applied to the writing device 15A pushes the domain wall 1420 in very close proximity to the magnetic shift register 10, enhancing the effect of the fringing field from the domain wall 1420.

In another embodiment, shown in FIG. 15 (FIGS. 15A, 15B), the arch-shaped bend 1405 of FIG. 14 is replaced with a small ferromagnetic (or ferrimagnetic) block 1505. A thin layer 1510 is formed on top of the ferromagnetic block 1505. The thin layer is used to determine the spacing of the ferromagnetic material 1505 from the track 10. Since the writing device is preferably not in electrical contact with the shift register, the thin layer 1510 may be formed from an insulating material that is contiguous with the insulating material surrounding the writing device 15B and the shift register 10. The domain wall 1515 is pushed to the middle of ferromagnetic block 1505 by the current 1520.

In a further embodiment, the homogeneous ferromagnetic material in the writing device 15C can be replaced by inhomogeneous material, as shown in FIG. 16. Track 1605 of the writing device 15C is constructed of alternating types of ferromagnetic materials. For example, blocks 1605 and 1615 are one type of magnetic material, while block 1610 and 1620 are another type. Two or more types of ferromagnetic materials may be used in various positions in the track 1605. These alternating types of ferromagnetic materials serve to create defined regions in which the domains in the track 1605 reside, minimizing drift

and allowing higher tolerance in current amplitude and pulse width, as presented earlier.

The magnetic moments of blocks 1610 and 1615 are aligned in the same direction so that no fringing fields are applied to the magnetic shift register 10 when the writing device 15C is in the quiescent state. Otherwise, fringing fields 1625 and 1630 write to the magnetic shift register 10 when the proper current is applied to move the domains in the writing device 15C.

In this embodiment, the domain walls are moved so that they are situated under the track for a time determined by sequential current pulses 1520. The first pulse moves the domain wall fringing fields 1625 or 1630 underneath the track 11. The time delay before a second current pulse will determine how long the domain wall fringing field is allowed to write the track 11.

In another embodiment, the magnetic regions or domains 1610 and 1615 can be combined and formed from one magnetic material. The magnetic regions1605 and 1620 can also be formed from an alternate magnetic material, since there is no need to have a means of providing a pinning potential for the domain wall underneath the track 10. The writing of the track 10 can be performed by simply passing the domain wall and its associated fringing field underneath the track 10 without stopping under the track.

The effect of inhomogeneous material may be created by introducing indentations 1725, 1726, 1727 in the track 1705 of the writing device 15D, as shown in FIG. 17. These indentations 1725, 1726, 1727 also serve to fix the regions in which the domains in the track 1705 reside. The indentations 1725, 1726, 1727 can be of any physical form that provides a pinning potential for the domain walls.

As shown in FIG. 17, the indentations (or protuberances) 1725, 1726, 1727 are disposed on top of the writing element track. Alternatively, they can be on one side or both sides of the writing device's track. Similarly, the indentations can be replaced with arch-shaped regions in the wire, as indicated by the reference numeral 1405 in Fig. 14B. Alternatively, the indentations 1725, 1726, 1727 can be combined with an-arch shaped region in the vicinity of the magnetic shift register 10 for increasing the magnitude of the domain wall fringing field provided at the magnetic shift register.

The indentations 1725, 1726, 1727 are placed between domains 1705, 1710, 1715, and 1720. In the present illustration, indentation 1726 is placed below the magnetic shift register 10, to fix the placement of fringing fields 1730 and 1735 that are used to write to the magnetic shift register 10. When an appropriate current is applied to the writing device 15C, the fringing fields 1730 and 1735 move to indention 1726, allowing precision placement of the fringing field. In a further embodiment, the reading device may be made of a combination of different ferromagnetic materials with indentations, combining the features of magnetic shift register 15C and 15D.

In another embodiment, no indentation is made under the shift register 10. The writing of the shift register is achieved simply by moving the domain walls and their associated fringing fields under and across the shift register 10 without ever having the domain walls stationary underneath the shift register.

The local magnetic fields of the fringing fields can be very large and can approach the magnetization of the material, $4\pi M$. In disk drive writing heads, the maximum achievable field is $4\pi M$ of the magnetic disk material. Disk drive

development seeks to make the magnetization larger, making larger magnetic moments and larger fields to ensure adequate writing to the disk.

In the present writing device, the magnitude of the domain wall fringing fields is related to the magnitude of the material used in the writing device. Local fields of several thousand oersteds are achievable. Consequently, the writing device can write strongly and reliably to the magnetic shift register 10. The width of the writing device is the width of the domain written on the magnetic shift register 10. In one embodiment, the typical width of the writing device is 100 nm in size.

A device similar to a magnetic tunneling junction can be used to read the information stored on the magnetic shift register 10. A magnetic tunneling junction (MTJ) (also referred to herein as the reading device) has two layers of magnetic material separated by a thin layer of insulating material which comprises a tunneling barrier. This tunneling barrier is typically formed from an ultra thin layer of aluminum oxide although it can also be formed from other insulating or semiconducting materials.

One magnetic layer in the MTJ is typically a hard magnetic material that requires a large magnetic field to change its magnetization; this layer is the "pinned" magnetic layer. The other magnetic material is typically a soft magnetic material, allowing a weak magnetic field to change its magnetization; this layer is the "free" magnetic layer. When a small magnetic field is applied to the soft magnetic material, its direction of magnetization changes so that the direction of the magnetization of the soft magnetic layer can be varied relative to that of the hard magnetic material.

The magnitude of the current passed through the tunneling barrier depends on the relative magnetic orientation of the two magnetic materials in the tunneling junction. Consequently, the value of the current in the tunneling junction indicates the direction of the magnetic moment in the soft magnetic material if the moment of the hard layer is known or the current in the tunneling junction indicates the direction of the moment of the hard magnetic material if the direction of the moment of the soft magnetic material is known.

The two magnetic materials in the magnetic tunneling junction can also be formed from hard magnetic materials if means for independently switching the magnetic moments in the MTJ are provided. The tunneling current passing through the MTJ allows the direction of the magnetic moment of either one of the two magnetic materials in the MTJ, i.e., the storage or sensing layer, to be determined if the direction of the magnetic moment of the other material, i.e., the reference layer, is known.

By incorporating the magnetic shift register 10 as part of the magnetic tunneling junction, information stored in the domains in the magnetic shift register 10 can be read in terms of the magnitude of the current that passes through the magnetic tunnel junction. However, the magnetic tunnel junction device is difficult to fabricate since the tunnel barrier of the MTJ is formed from an ultra thin insulating layer just a few atomic layers thick. Therefore, it may be advantageous to form a magnetic tunnel junction reading device which is both electrically isolated from the magnetic shift register and magnetically separated from the magnetic shift register track. An exemplary reading device of this type is shown in FIG. 18 (FIGS. 18A, 18B).

The device is comprised of a current conductor 1805, an antiferromagnetic layer 1810, a reference magnetic layer 1815 (also referred to as a pinned layer

1815), a tunneling barrier 1820, a soft magnetic layer 1825 (also referred to as a free layer 1825), a capping layer 1830, a current conductor 1835, and an insulating layer 1840. The reference magnetic layer 1815 may also be formed from a hard magnetic material whose magnetization direction is set in a given direction during the process of fabricating the magnetic shift register memory device. In this case the antiferromagnetic exchange bias layer 1810 is not required.

The fringing fields, such as fringing fields 1850, 1855, 1860, indicate the direction of the magnetic moments in the domains of the magnetic shift register 10. As the fringing fields 1850, 1855, 1860 move across the reading device 20, the direction of the magnetic moment in the free layer 1825 is aligned in the same direction as the fringing field 1850, 1855, 1860.

Current flow in the reading device 20 is further illustrated by the diagram of FIG. 19, where the magnetic shift register 10 is shown in dashed lines. The current 1845 applied to the reading device 20 is represented by an arrow. The current 1845 is applied to the current conductor 1805, flowing through the reading device 20 to the current conductor 1835. Insulating layer 1840 electrically insulates the magnetic shift register 10 from the current conductor 1835.

When the magnetic moments of the free layer 1825 and pinned layer 1815 are parallel, the resistance of the reading device 20 is low. Conversely, when the magnetic moments of the free layer 1825 and pinned layer 1815 are anti-parallel to each other, the resistance of the reading device 20 is high. The magnetic tunnel junction can also be designed so that the resistance is highest when the magnetic moments of the free and pinned layers are parallel to one another but the principle of operation of the reading device is the same.

The relative alignment of the pinned layer 1815 and free layer 1825 can thus be determined by, for example, passing a current through the reading device 20 and measuring the resulting voltage or potential. A low voltage implies low resistance: the pinned layer 1815 and free layer 1825 are in parallel alignment. A high voltage implies high resistance: the pinned layer 1825 and free layer 1815 are anti-parallel. Consequently, the voltages measured from the reading device 20 indicate the direction of the magnetic fringing fields in the domain walls of the magnetic shift register 10, thereby indicating the data stored in the magnetic shift register 10.

The reference layer 1815 can be formed from a magnetic material which is soft such as Ni, Co or Fe or a binary or ternary alloy formed from two or more of Ni, Fe and Co. The magnetic moment of the reference layer 1815 using a soft magnetic material is fixed or pinned in a particular direction by using the well known phenomenon of exchange bias and exchange coupling the reference layer 1815 to the material of the antiferromagnetic layer 1810. The antiferromagnetic layer 1810 can be formed from various alloys including alloys of Mn with Fe, Ni, Ir, Pt, Pd, Cr, etc.

Alternatively, the reference layer 1815 can be formed from a magnetic material which is sufficiently hard that its moment direction is not affected by the fringing fields from the domain walls in the magnetic shift register as the domains are moved around the magnetic shift register. For example, the reference layer 1815 is formed from alloys of Co and/ or Fe and Pd and Pt or alloys of rare-earth metals and transition metals such as alloys formed from Co, Fe and Tb.

In this embodiment, the reading device 20 does not touch the magnetic shift register 10, and may be placed in any orientation or distance at which the fringing field 1855 may still consistently change the orientation of the free layer 1825.

A method 2000 used by the writing device 20 to read data stored on the shift register 10 is described by the process flow chart of FIG. 20. A magnetic memory system selects a bit to read (block 2005). At block 2010, the magnetic shift register 10 moves the corresponding domain wall to the reading device as described in connection with FIG. 3.

If the magnetic fringing field associated with the domain wall of interest points right, for example, the magnitude of the current induced in the reading device 20 may be large, otherwise, the magnitude induced in the reading device 20 is small. The reading device may be configured that the opposite case is true. Either way, the magnitude of the current can be used to determine the direction of the magnetic fringing field associated with the selected domain wall.

At block 2015, the magnetic memory system measures the current induced in the reading device, and determines the direction of the magnetic fringing field from the current value at block 2020. The current in the reading device 20 flows from the current conductor 1805 through the reading device 20 to the current conductor 1835. The magnetic fringing field direction represents the state of the domain wall between the magnetic domains stored in the magnetic shift register 10. The directions used for magnetic fringing field and current used to describe the present illustration are only of exemplary nature.

In the preceding figures, such as FIG. 1, the shift registers are shown as being above the reference plane of circuitry including the reading and writing

elements. Alternatively, the shift registers may be disposed beneath the plane of circuitry.

Although the orientation of the magnetic moments of the free and pinned magnetic moments in FiG. 18 are shown as being parallel to the magnetic medium the magnetic moments of the pinned and free layers of the data reading device can also be oriented perpendicular to the magnetic medium. Similarly, the magnetic moment direction of the free and pinned layer moments can be oriented perpendicular to the current flowing through the data reading device.

The data reading device described herein has been described particularly with reference to the magnetic shift register. However, the data reading device can also be used to read magnetic bits stored in magnetic media in conventional magnetic recording disk drives, which utilize either longitudinal or perpendicular recording technologies. Similarly, the data reading device of this invention can be used to read the state of magnetic domains, or their associated magnetic domain wall fringing fields in any magnetic storage device or other magnetic device. For example, the data reading device described herein could be incorporated as part of a magnetic isolator to transpose information or signals stored statically or dynamically within a magnetic medium to a voltage or current signal.

It is to be understood that the specific embodiments of the invention that have been described are merely illustrative of certain applications of the principle of the present invention. Numerous modifications may be made to the system and method for reading data stored on a magnetic shift register invention described herein without departing from the spirit and scope of the present invention.